Some Contemporary Advances in Physics

By K. K. DARROW

NOTE: Dr. Darrow, the author of the following article, has made it a practice to prepare abstracts and reviews of such recent researches in physics as appear to him to be of special interest. The results of Dr. Darrow's work have been available to the staffs of the Bell System laboratories for some time and having been very well regarded, it is thought that such a review, published from time to time in the TECHNICAL JOURNAL, might be welcomed by its readers.

The review cannot, of course, cover all the published results of physical research. The author chooses those articles which appear significant to him or instructive to his readers, without attempting to pass judgment on the scientific importance of the different papers published. It is not intended that the review shall always assume the same form; at one time it may cover many articles, at another be devoted to only a few, and it may occasionally treat of but a single piece of work.—*Editor.*

SOME years ago C. T. R. Wilson of Cambridge University developed a beautiful method for making the paths of moving charged atoms and electrons individually visible. The charged particle flies through a gas such as air, mixed with water-vapor; it ionizes many of the molecules near which it passes; the gas is suddenly cooled by expansion and the water-vapor is precipitated upon the ionized molecules, forming a trail of droplets which visibly mark out the path of the ionizing electron or atom. Truly spectacular photographs of such trails, thick straight ones of fast-moving atoms and thin curly ones of electrons, are frequently published in textbooks and in popular articles.

The method is now proving very powerful in the study of collisions and close encounters of electrons with atoms and of atoms with atoms. Rutherford having found by another method that the nuclei of atoms are occasionally broken up by unusually direct blows from fast-moving helium nuclei (alpha-particles), the prospect of actually photographing such an important event becomes alluring. However, it is a very rare event; for W. D. Harkins and R. W. Ryan of the University of Chicago photographed eighty thousand alpha-particle trails in air, and only three of the particles struck molecules so squarely as to be deflected through more than a right angle; and of these only one showed indications of having broken the nucleus it struck. This particular collision is shown in Fig. 1 (two photographs of the same encounter taken from different directions at the same moment). In addition to the tracks of the alpha-particle up to and away from the scene of the encounter, there are two more tracks diverging from it, which are probably the tracks of two fragments of the struck nucleus. Other interpretations, such as two distinct impacts very near together or a stray radioactive atom

happening to disintegrate just as the alpha-particle passed by, are admissible but highly improbable. Another such collision in argon is shown in Fig. 2; this too was the only encounter with four diverging

Fig. 1

tracks observed in many thousand photographs with the same gas.[1] A collision in air, in which the struck nucleus was not broken, but knocked to one side while the alpha-particle rebounded in the manner demanded by the principle of conservation of momentum, is shown

Fig. 2

in Fig. 3. These results show how small the atom-nuclei must be, compared to the extension of their electron-systems; for the 80,000 alpha-particles observed in air had traversed the electron-systems of about ten billion molecules altogether.

[1] As Rutherford's experiments indicate that argon atoms are especially stable against disintegration, this may be a case of two consecutive collisions with adjacent atoms.

Fig. 4 shows curious collisions of alpha-particles passing through helium gas, photographed by D. Bose and S. Ghosh of Calcutta. In each of the two left-hand trails the alpha-particle has apparently

Fig. 3

knocked the nucleus and the two electrons of the atom in three different directions.[2] The alpha-particle of the right-hand trail (*iiib* is a magnification of *iiia*) seems to have produced quite an explosion; this may be the disruption of a nucleus belonging to a stray molecule

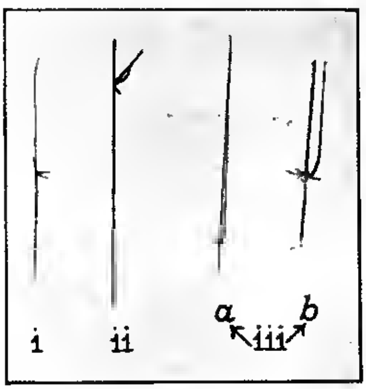

Fig. 4

of nitrogen, but one would not expect the original particle to go on as if unaffected.

[2] In hydrogen they found no cases of two electrons being driven off by the same impact. This agrees with Millikan's conclusion that double ionization is much more frequent with helium atoms than with molecules of any other kind, if indeed, it is not a characteristic of helium alone.

Much work is now being devoted to the spectra of ionized atoms. One instance, that of ionized potassium, will suffice to illustrate the problem. The potassium atom differs from the argon atom in three respects; the weight of its nucleus is slightly different, which is probably inessential; the charge on its nucleus is 19/18 as great; and it has a nineteenth electron outside of the three closed electron-shells, comprising eighteen electrons, which by themselves constitute the whole electron-system of the argon atom. When this outermost electron is removed, we have a system which probably differs from the argon atom in only one essential respect—that the central nucleus has a somewhat larger attractive power and hence the three electron-shells are somewhat more drawn inward. The spectra of ionized potassium and of argon should therefore be very nearly alike. This has been tested by Zeeman and Dik at Amsterdam; the result is very satisfactory, and the difference between the simple and clearly-arranged spectrum of potassium on the one hand, and the rich and intricate spectra of ionized potassium and argon on the other hand, is very striking. At Bonn, the spectrum of ionized rubidium is being compared with that of krypton for the same purpose.

The most extensive results, however, have been obtained by Fowler with silicon. For some reason or other, silicon is a particularly easy element from which to obtain spectra not only of the neutral and the ionized atom, but also of the twice-ionized and thrice-ionized atom—four distinct spectra, one from neutral silicon, the next from an atom resembling aluminium, the next from an atom resembling magnesium, and the last from an atom resembling sodium. These four spectra can be observed in the stars and in the laboratory, some of the important lines from thrice ionized atoms having been photographed by Millikan in the extreme ultra-violet. In their general type, they resemble the spectra of the neutral atoms corresponding in structure to the atoms which emit them.

Data have also been made available for doubly-ionized magnesium (by Paschen) singly-ionized magnesium, and for neutral sodium—three atoms in which the nuclear charge is respectively 13e, 12e, and 11e, while in each of them the nucleus is surrounded by ten electrons and there is an eleventh one much further out. This eleventh electron being responsible for the spectrum and being relatively exempt from perturbations due to the other ten, the spectra of these three atoms are of the simplest and clearest type. The series-lines which in the spectrum of neutral sodium are in the inaccessible infra-red are moved up, in the spectrum of doubly-ionized aluminium, into the visible region. Further study of spectra related to each other in this

manner, and differing by virtue of slight intelligible differences in the atoms which emit them, may be expected to help greatly in making clear the major features of atomic structure.

Two phenomena, first accurately examined by A. H. Compton, afford a striking illustration of the way in which classical electromagnetic theory and quantum theory are alternately successful in explaining the qualities of radiation. On the one hand, Compton has been the first to apply accurate wave-length measurements to scattered X-rays, and finds that they are a mixture of two kinds of X-rays—one having exactly the same wave-length as the primary X-rays, the other a wave-length slightly greater and varying with the angle between the primary and the secondary rays. According to the classical theory, scattered X-rays are simply radiation sent out in all directions by electrons inside the atoms of the scattering substances, vibrating under the influence of the primary X-rays, and hence vibrating necessarily with the same frequency as the primary X-rays. This could account for one of the components of the scattered X-rays, but not the other. The other can be accounted for by assuming that the primary X-ray quanta of frequency n are perfectly elastic spheres which travel with the velocity of light, have momentum hn/c and energy hn, and collide with the atoms just as one elastic sphere collides with another (that is, under conditions of conservation of translatory kinetic energy and of momentum); they depart from the collision with less energy and less momentum than they initially had, and consequently with a diminished frequency. But this does not explain the first-mentioned component, leaving the two theories balanced. On the other hand, in the *Philosophical Magazine* paper, Compton describes the total reflection of X-rays by glass, silver and lacquer—a phenomenon of exactly the type which the classical theory explains far more easily and naturally than the quantum-theory.

In glass and lacquer, the highest natural frequency of any of the electrons in any of the constituent atoms—to speak the language of the classical theory—is far below the frequency of available X-rays; we are, in optical terminology, on the high-frequency or anomalous-dispersion side of the highest-frequency absorption-band; the well-known dispersion formula reduces to a single term,

$$\mu = 1 - Ne^2/2\pi mn^2$$

where N is the total number of electrons able to vibrate in unison with the X-rays, and μ is the index of refraction of the X-rays of

frequency n; e and m have their usual meanings. The index of refraction is less than unity, the X-rays travel faster in glass or in lacquer than in air or in vacuo, and are totally reflected from a glass surface if incident at a sufficiently small angle with the surface. The agreement between experiment and theory is, quantitatively as well as qualitatively, very good. It is equally good for silver, allowance being made for the fact that the frequency of the X-rays used lay between the two absorption-bands of silver. It seems conceivable that this might be refined into a method for determining the numbers of electrons in different orbits of the atom.

The atoms of the inert or "rare" gases argon, krypton, and xenon are almost completely transparent to slow electrons—electrons moving with a speed of one or two equivalent volts. In more exact language, the radius of the effective cross-section of one of these atoms relatively to slow electrons is much smaller than its radius relatively to faster electrons or to other atoms. This almost incredible statement, having been tested by several different experimenters and by at least two entirely distinct methods, now appears to stand beyond doubt. This radius of the effective cross-section of the atom, relatively to an electron, is (by definition) the least distance at which the electron can pass by the centre of the atom without being intercepted or deflected; the radius of the atom relatively to another of the same kind is, naturally, half the least distance at which the centres of the two atoms can pass each other without affecting one another's paths. The concept is not perfectly exact, depending as it does on what we choose to take as the least perceptible alteration of the path of a particle; nevertheless, it is practicable and useful. Years ago the radius relative to other atoms was determined (from the viscosity of the gas). There is no binding reason why it should be identical with the radius relative to electrons, but the first measurements of this latter quantity on such gases as hydrogen, nitrogen, and helium yielded fairly good agreements between the two. Recent measurements on argon disclosed a surprising difference.

The method consists essentially in measuring the fraction of a beam of electrons, projected against a layer of gas, which pass through the layer undeflected. (Another and entirely different method used by Townsend resulted in a valuable confirmation of the result.) If there are N atoms under unit area of the surface of the layer (looking through it in the direction from which the electrons come) and N is not so large that many of the atoms are partly shielded, in the perspective, by others, the fraction of the electrons which go through undeviated is $(1-N\pi r^2)$; r being the radius just defined. The most

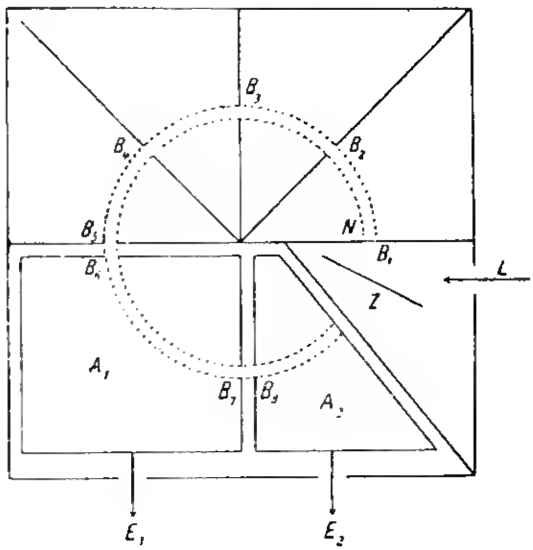
B_3
B_4
B_2
B_5
N
B_1
B_6
L
Z
A_1
B_7
B_8
A_2
E_1
E_2

Fig. 5

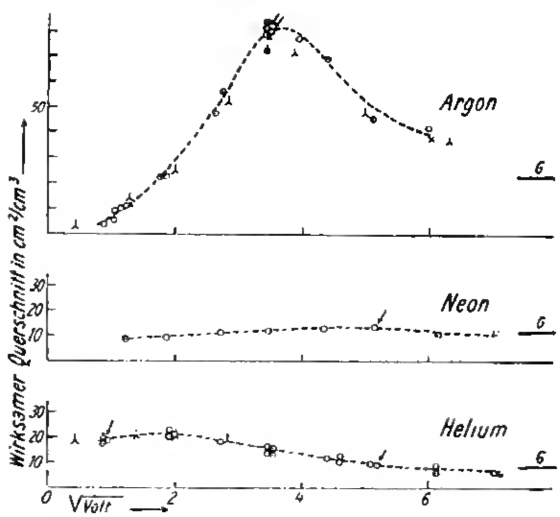
Argon
Neon
Helium
Wirksamer Querschnitt in cm²/cm³
√Volt
0
2
4
6
50
30
20
10

Fig. 6

delicate arrangement is that of Ramsauer (Fig. 5); the electrons enter at B_1, and are steered by a magnetic field along a semicircular path through the slits $B_2 - B_8$; electrons deviated even through a very slight angle go against the partitions and are not received by the electrometers connected at E_1 or E_2. Measurements with the two

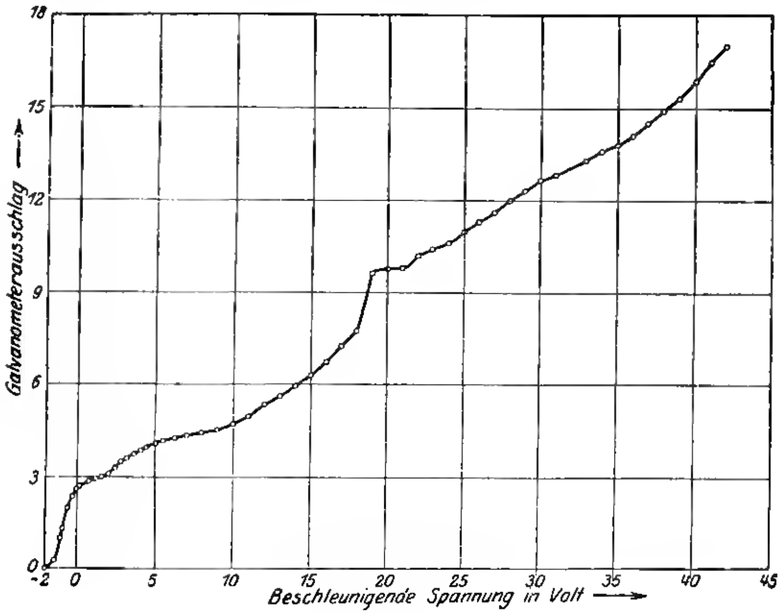

Fig. 7

electrometers, at two pressures of the gas, yield the data required. The values of r^2 thus determined for argon, neon and helium are plotted against the speed of the electrons in Fig. 6. The ordinates of the short straight horizontal lines on the right represent the squares of the radii relatively to other atoms.

The effect shows itself, however, very distinctly in a much simpler and more common device, a cylindrical three-element tube of audion type with the grid very much closer to the filament than is the plate; the plate is maintained at a potential a fraction of a volt higher than that of the grid. Figs. 7 and 8, from a recent article by Minkowski and Sponer, exhibit curves of plate-current versus grid-voltage in helium, which does not show the effect in question, and argon, which does.[3] In helium the current rises steadily as the increasing voltage

[3] The displacement of the curves by about −2 volts along the axis of voltages is probably due in part to drop of potential along the filament, in part to neglected contact-potential-differences.

gradually overcomes the space-charge repulsion, augmented in the gas by the reflection of electrons, for the reflected electrons stay longer in the space between filament and plate than they would if they went straight through. In argon the curve rises at first more swiftly, almost or quite as steeply as in vacuo, for the atoms are almost transparent to the electrons when they are slow; but as their speed is increased and the effective radius of the atom rises, the current sharply declines again. Further on, near 11 volts, there is

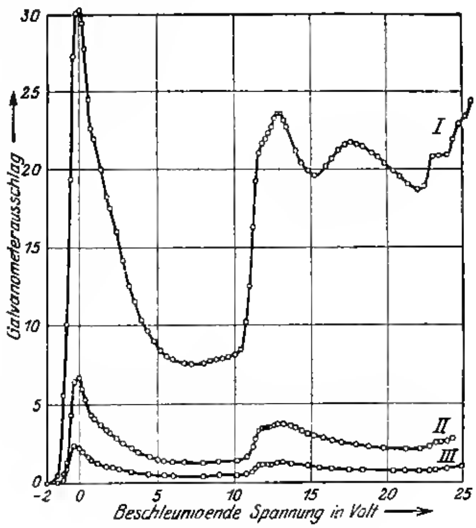

Fig. 8

another peak; near this voltage, the electrons which collide with atoms lose almost all their energy (threshold-speed for inelastic impact at 11.3 equivalent volts) at the first collision, and pass through the rest of the gas-filled region without obstacle. A second peak near 16 volts is ascribed to a second critical speed for inelastic impacts. Krypton and xenon give toothed curves of the same general type. Neon and mercury vapor, however, behave like helium, the curves rising steadily or at most showing slight kinks and inflections which may be indications of a slight effect of the same sort.

The reason for this remarkable effect is still obscure. It may be possible to devise an atom-model adequate to explain it without forfeiting spherical symmetry, which it is desirable to retain if possible, for among all atoms these of the heavy inert gases would be

expected to display the most complete symmetry and smoothness. F. Hund tried to devise an atom such that any one-volt electron passing within a distance r of the centre would be deflected through exactly 360° before coming out; he attained a formal solution of the problem, but the model involved a continuous distribution of negative charge from the nucleus outward to the distance r, which is quite incompatible with all our other knowledge of atomic structure. H. A. Wilson of Rice Institute tried out a well-known and popular model, consisting of a nucleus surrounded by a spherical surface of radius r, over which negative charge equal in amount to the positive charge on the nucleus is uniformly spread. For very slow electrons, the average angle of deflection is 90°; it increases with speed, becoming 180° at a certain critical value v_0 at which every electron is turned back into the direction whence it came; beyond v_0 it decreases indefinitely with increasing speed. At v_0 the oncoming electrons are more radically deflected by the atoms, so to speak, than at any greater or lesser speed; below v_0 the variation of mean deflection with speed is in the proper sense to agree with experiment, but not by any means of a sufficiently great order-of-magnitude. The theory, however, seems to explain the mild variations encountered in such gases as hydrogen and nitrogen, and the explanation of the more striking ones may lie in the same direction.[4]

Important contributions have lately been made to our knowledge of self-sustaining discharges, such as the glow and the arc, which maintain themselves as long as the proper voltage is applied at the electrodes, without requiring the assistance of a separate source of ions such as a hot filament or an outside ionizing agency such as X-rays. The field has perhaps been somewhat neglected, because it is easier to obtain simple clear results with electrons and ions admitted into a very rarefied gas after being generated elsewhere. In a self-sustaining discharge, there is usually a sudden steep potential-drop just in front of the anode, and another just in front of the cathode—the so-called anode-fall and cathode-fall; in the region between, the potential varies gradually. The anode always tends to become very hot, and Gunther-Schulze at Berlin has lately measured the rate at which heat is generated at the anode of a mercury arc; he finds that it agrees wonderfully well with the rate calculated from the assumption that practically the entire current is carried by negative ions

[4] Any competent theory must explain the results obtained by different methods, notably the fact that the value of r measured in an apparatus like Ramsauer's agrees with the value measured in an apparatus in which electrons deflected through considerable angle should yet reach the collector, and so be counted as though they had not been deflected at all.

(probably electrons) which dash against the anode with the entire kinetic energy acquired during unobstructed passage through the anode-fall.[5]

The heat generated at the cathode must arise in the converse way, from the kinetic energy of positive ions pulled violently against the cathode surface. K. T. Compton of Princeton, has made elaborate calculations for the arc in air with a carbon cathode and the arc in hydrogen with a tungsten cathode, and comparing the results with the experimental evidence, concludes that a few per cent of the current at the cathode is carried by positive ions, the remainder by electrons moving away from the cathode. Compton then attacked the same problem in an entirely different manner; he assumed that the region near the cathode, in which the cathode-fall occurs, is a region in which positive ions are moving gradually towards the cathode, accelerated by the field, and retarded by their collisions with neutral molecules and by their mutual space-charge repulsion. The problem is formally similar to that of determining the current-voltage relation in a thermionic vacuum-tube, and the solution is a relation between cathode-fall, current, and width of the region in which the cathode-fall occurs. The first quantity is known; the third is assumed to be the mean distance which an electron travels from the cathode before striking a molecule; the second quantity, the current of positive ions into the cathode, comes out to be a few per cent of the observed total current. These two methods thus support one another in indicating that in the arc-discharge some 90–98% of the current near the cathode is carried by electrons, and the small remainder by positive ions. In the glow-discharge, according to experiments by Gunther-Schulze, the rate at which heat is generated at the cathode is 25% to 75% of what it would be if all the current were carried by positive ions, falling against the cathode with the entire energy derived in passing through the cathode-fall. Expecting that a much larger fraction of the energy of the positive ions would be dissipated in collisions with neutral gas molecules, he concludes that the region of the cathode-fall must be a region in which the gas is abnormally rarefied because abnormally hot; the hotness in turn being due to the collisions between ions and molecules.

In the central region of the arc, the potential-gradient is uniform and consequently the positive and negative charges per unit volume

[5] It is obviously necessary to be very cautious in making deductions of this kind, for the entire energy iV (i representing the current and V the anode-fall or cathode-fall, as the case may be) is dissipated as heat in the region of the anode-fall or cathode-fall; and if this region is very narrow it is hard to distinguish between heat generated within it and heat generated at the anode or cathode surface.

must exactly balance one another. In this region Compton suggests that the gas is in the state of thermal ionization defined and described by Saha, in which at all times a certain constant percentage of the atoms, depending only on their ionizing-potential and on the temperature, is ionized. If the temperature of the central region of the carbon arc is about 4000°, and the ionizing-potential of the gas about 8 volts, the proportion of ionized molecules will be about right.

According to one of the newer and stranger developments of the quantum-theory, an atom possessing magnetic moment and submerged in a magnetic field is not at liberty to orient itself in any direction whatever, not even momentarily; it may set itself only at certain specified inclinations, such that the cosine of the angle between the direction of its magnetic axis and the direction of the field will have one of certain specified values. Imagine for example, an atom consisting of a single electron revolving in a one-quantum orbit (the smallest possible orbit) about a centre which itself is not magnetic; such a centre might be a simple nucleus, or a nucleus surrounded by a number of electrons moving in orbits so inclined to each other that their magnetic moments cancel one another out. The magnetic moment of such an atom is $eh/4\pi m$ (e the charge and m the mass of the electron); its magnetic axis is perpendicular to the plane of the orbit of the electron. According to the theory, the magnetic axis must point exactly with or exactly against the magnetic field; the cosine of the angle must be $+1$ or -1. This was verified last year by Gerlach, who projected a ray of silver atoms (shooting off from a hot rapidly-evaporating silver filament through a small hole) across a magnetic field with an extremely steep field-gradient. The ray divided itself into two, one consisting of atoms with their north magnetic poles pointing directly up the field, the other of atoms turned through 180° relatively to the first set; there was quantitative agreement with the theory. If the outside electron moves in a two-quantum orbit, the magnetic moment of the atom is $2\ eh/4\pi m$, and the cosine of the angle may take the values ± 1 and the values $\pm \frac{1}{2}$; if in a n-quantum orbit, the moment is $neh/4\pi m$ and the permissible values for the cosine are $\pm 1/n$, $\pm 2/n$, ... $\pm n/n$.[6]

The theory also accounts for the normal Zeeman effect. It remains to be settled whether the magnetic moments of actual paramagnetic substances can be calculated from it. According to the accepted

[6] The condition governing the angle is, that the integrals of (a) the angular momentum of the electron in its orbit, and (b) the projection of the angular momentum on the plane normal to the field, taken around a complete cycle of the orbital motion, must both separately be integer-multiples of the quantum-constant h. The latter integer-multiple cannot be zero, according to Gerlach's experiment and Sommerfeld's theory.

belief, the atoms of a paramagnetic substance all have a given constant magnetic moment, but are oriented in every possible direction so that the resultant magnetic moment of any piece of the substance is zero. If all the atoms could be made to point in the same direction by a powerful magnetic field, the total moment of the piece would be equal to the number of atoms in it multiplied by the moment of each atom, which could then be determined. No attainable magnetic field is strong enough to do this; the persistent effort of the field to twist the atoms into parallelism is almost completely counterbalanced by the thermal agitation. The total moment of the piece when all the atoms are parallel, and therefore the moment of each atom, have therefore to be calculated from the trend of the magnetization-versus-field strength curve in its attainable portion. In making this calculation it has heretofore been assumed that all orientations of the atoms are possible. Replacing this assumption by the contrasting one explained in the foregoing, we find the method of calculation altered;[7] the data heretofore assembled remain valid, but the values of magnetic moment computed from them are replaced by an entirely new set.

The old set of values of magnetic moment, calculated for a number of solid and gaseous substances and of ionized liquids, by Weiss and others, were said to be integer multiples of a fundamental constant, the "Weiss magneton." No one had succeeded in calculating the observed value of this constant from any atomic theory, and it is not compatible with the picture of the atom given above. The new set of values, according to Gerlach and to Pauli, who have worked over the published experimental material, is compatible with the atom-model. The values for solid platinum and palladium; for nickel in its high-temperature non-ferromagnetic "beta" form; and for nitric oxide gas, agree with the simplest model—the electron in a one-quantum orbit revolving around a non-magnetic centre. The value for gaseous oxygen agrees with the model having an electron in a two-quantum orbit; gamma-iron with the three-quantum, Mn_2O with the 4-quantum and MnO with the 5-quantum model. Various ions in solution from Cabrera's data also give values in accordance with the theory. It is implied that these cover all the reliable ob-

[7] In the latter case it is assumed that the number of atoms oriented with their axes in one permissible direction D_1 stands to the number oriented in another permissible direction D_2 in a ratio given by $exp\ (W/kT)$ where T is the temperature, k is Boltzmann's constant, and W is the work required to twist an atom from direction D_1 to direction D_2 against the magnetic field. In the former case all directions are regarded as permissible, and in the assumption just stated, "number of atoms oriented in direction D" is replaced by "density in solid angle of atoms oriented in direction D," a fundamental change.

servations on paramagnetic substances, except for two ions which yield values not reducible to agreement with the new theory.[8] The new method of calculating magnetic moments thus leads to values which confirm the contemporary atom-model. It would not be desirable to dismiss the old method and the old theory too hastily, considering that they lead to values which are claimed to be integer multiples of an apparently fundamental constant; but this constant has proved so intractable to theory that it would be gratifying to be able to discard it.

The arrangement of atoms in two samples of Heusler alloys was investigated with the X-ray method by J. F. T. Young at Toronto. These alloys are mixtures of the metals, copper, manganese, and aluminium in certain proportions; they are strongly ferromagnetic while the component metals are not ferromagnetic at all. Of the two samples, one had a much higher permeability than the other; the atoms of the former sample were arranged in a body-centered cubic lattice, with no trace of the characteristic lattices of the component metals. The atoms of the latter sample were arranged in a face-centred-cubic lattice. Thus these alloys furnish an additional instance of the frequent, though not by any means universal, correlation between body-centred-cubic lattice and strong ferromagnetism. L. W. McKeehan of the Western Electric used the same method to investigate palladium containing great quantities of occluded hydrogen. The space-lattice of the hydrogen-free metal was distended by a certain fixed percentage by saturating it with hydrogen; and it appeared that when the palladium contained a lesser quantity of hydrogen than the maximum or saturation amount, some parts of it were quite saturated and others contained no hydrogen at all, instead of the whole lattice being equally enlarged; it is probable that the individual crystals of the metal are saturated one by one as the hydrogen creeps in.

[8] The value for beta-iron as quoted by Gerlach does not agree with the theory. As for the values assigned by Weiss to the three ferromagnetic metals iron, nickel and cobalt, obtained from direct measurements of the saturation-intensity at the temperature of boiling hydrogen, the first two do not agree with the theory, the last agrees very well (assuming the electron to be in a one-quantum orbit). Of course, it is likely enough that the theory should not be applied to ferromagnetics. It seems fitting to quote a remark of Andrade about theories of magnetism in general " . . . the substances selected for verification of theories are of a very limited class, called of normal behavior rather because they agree with the theories than because they represent a numerical majority."

REFERENCES

D. M. Bose and S. K. Ghosh: *Nature* 111, pp. 463–464; 1923.

A. H. Compton: *Physical Review*, 2d ser., 21, pp. 483–502 and 715; 1923. (X-ray scattering.)

A. H. Compton: *Philosophical Magazine*, 43, pp. 1121–1129; 1923. (Total reflection of X-rays.)
K. T. Compton: *Physical Review*, 2d ser., 21, pp. 266–291; 1923.
W. Gerlach: *ZS. für Physik*, 9, pp. 349–355; 1922. (Magnetic moment of silver atoms.)
W. Gerlach: *Physikalische ZS.*, 24, pp. 275–277; 1923.
H. Gunther-Schulze: *ZS. für Physik*, 15, pp. 8–23; 1923. (Cathode-fall.)
H. Gunther-Schulze: *ZS. für Physik*, 13, pp. 378–391; 1923. (Anode-fall.)
W. D. Harkins and W. H. Ryan: *Journal Am. Chem. Soc.*, 45, pp. 2095–2107; 1923.
F. Hund: *ZS. für Physik*, 14, pp. 241–263; 1923.
L. W. McKeehan: *Physical Review*, 2d ser., 21, pp. 334–342; 1923.
R. Minkowski and H. Sponer: *ZS. für Physik*, 15, pp. 399–409; 1923.
F. Paschen: *Annalen der Physik*, 71, pp. 142–161; 1923.
W. Pauli: *Physikalische ZS.*, 21, pp. 615–617; 1920.
C. Ramsauer: *Annalen der Physik*, 66, pp. 546–558; 1921.
H. A. Wilson: *Proc. Royal Society*, A103, pp. 53–57; 1923.
J. F. T. Young: *Philosophical Magazine*, 46, pp. 291–305; 1923.